

**AGILE and Fermi-LAT Observations of the "Soft" Gamma-Ray PSR B1509–58.**

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We present the results of  $\sim 2.5$  years *AGILE* observations of PSR B1509–58 and of the same interval of *Fermi*-LAT observations. The modulation significance of *AGILE* light-curve above 30 MeV is at a  $5\sigma$  confidence level and the light-curve shows a broad asymmetric first peak reaching its maximum  $0.39 \pm 0.02$  cycles after the radio peak plus a second peak at  $0.94 \pm 0.03$ . The gamma-ray spectral energy distribution of pulsed flux is well described by a power-law (photon index  $\alpha = 1.87 \pm 0.09$ ) with a remarkable cutoff at  $E_c = 81 \pm 20$  MeV, representing the softest spectrum observed among  $\gamma$ -ray pulsars so far. The unusual soft break in the spectrum of PSR B1509–58 has been interpreted in the framework of polar cap models as a signature of the exotic photon splitting process in the strong magnetic field of this pulsar. In the case of an outer-gap scenario, or the two pole caustic model, better constraints on the geometry of the emission would be needed from the radio band in order to establish whether the conditions required by the models to reproduce *AGILE* light-curves and spectra match the polarization measurements.

**I. INTRODUCTION**

PSR B1509–58 was discovered as an X-ray pulsar with the *Einstein* satellite and soon also detected at radio frequencies [26], with a derived distance supporting the association with the SNR MSH 15-52 ( $d \sim 5.2$  kpc). With a period  $P \simeq 150$  ms and a period derivative  $\dot{P} \simeq 1.53 \times 10^{-12} \text{ s s}^{-1}$ , assuming the standard dipole vacuum model, the estimated spin-down age for this pulsar is 1570 years and its inferred surface magnetic field is one of the highest observed for an ordinary radio pulsar:  $B = 3.1 \times 10^{13}$  G, as calculated at the pole. Its rotational energy loss rate is  $\dot{E} = 1.8 \times 10^{37}$  erg/s.

The young age and the high rotational energy loss rate made this pulsar a promising target for the gamma-ray satellites. In fact, the instruments on board of the *Compton Gamma-Ray Observatory* (*CGRO*) observed its pulsation at low gamma-ray energies, but it was not detected with high significance by the *Energetic Gamma-Ray Experiment Telescope* (*EGRET*), the instrument operating at the energies from 30 MeV to 30 GeV. This was remarkable, since all other known gamma-ray pulsars show spectral turnovers well above 100 MeV (e.g. [42]). Harding et al. ([17]) suggested that the break in the spectrum could be interpreted as due to inhibition of the pair-production caused by the photon-splitting phenomenon [3]. The photon splitting appears, in the frame of the polar cap models, in relation with a very high magnetic field. An alternative explanation is proposed by [50] using a three dimensional outer gap model. They propose that the gamma-ray emission is produced by synchrotron-self Compton radiation

above the outer gap.

The Italian satellite *AGILE* [41] obtained the first detection of PSR B1509–58 in the *EGRET* band (Pellizzoni et al. 2009b) confirming the occurrence of a spectral break. Here we summarize the results of a  $\sim 2.5$  yr monitoring campaign of PSR B1509–58 with *AGILE*, improving counts statistics, and therefore light curve characterization, with respect to earlier *AGILE* observations. More details on this analysis can be found in [35]. With these observations the spectral energy distribution (SED) at  $E < 300$  MeV, where the remarkable spectral turnover is observed, can be assessed.

**II. OBSERVATIONS, DATA ANALYSES AND RESULTS**

*AGILE* devoted a large amount of observing time to the region of PSR B1509–58. For details on *AGILE* observing strategy, timing calibration and gamma-ray pulsars analysis the reader can refer to [32, 33]. A total exposure of  $3.8 \times 10^9 \text{ cm}^2 \text{ s}$  ( $E > 100$  MeV) was obtained during the 2.5 yr period of observations (July 2007 - October 2009) which, combined with *AGILE* effective area, gives our observations a good photon harvest from this pulsar.

Simultaneous radio observations of PSR B1509–58 with the Parkes radiotelescope in Australia are ongoing since the epoch of *AGILE*'s launch. Strong timing noise was present and it was accounted for using the *fitwaves* technique developed in the framework of the TEMPO2 radio timing software [18, 19]. Using the radio ephemeris provided by the *Parkes* telescope, we

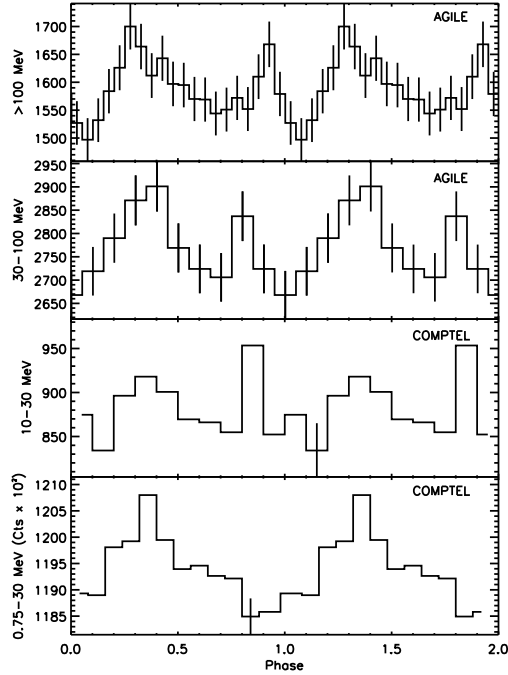


FIG. 1: Phase-aligned gamma-ray light curves of PSR B1509-58 with radio peak at phase 0. From the top: *AGILE*  $> 100$  MeV, 20 bins, 7.5 ms resolution; *AGILE*  $< 100$  MeV, 10 bins, 15 ms resolution; *COMPTEL* 10-30 MeV and *COMPTEL* 0.75-30 MeV (from [23]).

performed the folding of the gamma-ray light curve including the wave terms [33]. An optimized analysis followed, aimed at cross-checking and maximization of the significance of the detection, including an energy-dependent events extraction angle around the source position based on the instrument point-spread-function (PSF). The chi-squared ( $\chi^2$ )-test applied to the 10 bin light curve at  $E > 30$  MeV gave a detection significance of  $\sigma = 4.8$ . The unbinned  $Z_n^2$ -test gave a significance of  $\sigma = 5.0$  with  $n = 2$  harmonics. The difference between the radio and gamma-ray ephemerides was  $\Delta P_{radio,\gamma} = 10^{-9}$  s, at a level lower than the error in the parameter, showing perfect agreement among radio and gamma-ray ephemerides as expected, further supporting our detection and *AGILE* timing calibration.

We observed PSR B1509-58 in three energy bands: 30-100 MeV, 100-500 MeV and above 500 MeV. We did not detect pulsed emission at a significance  $\sigma \geq 2$  for  $E > 500$  MeV. The  $\gamma$ -ray light curves of PSR B1509-58 for different energy bands are shown in Fig. 1. The *AGILE*  $E > 30$  MeV light-curve shows two peaks at phases  $\phi_1 = 0.39 \pm 0.02$  and  $\phi_2 = 0.94 \pm 0.03$  with respect to the single radio peak, here put at phase 0. The phases are calculated using a Gaussian fit to the peaks, yielding a FWHM of 0.29(6) for the first peak and of 0.13(7) for the second peak,

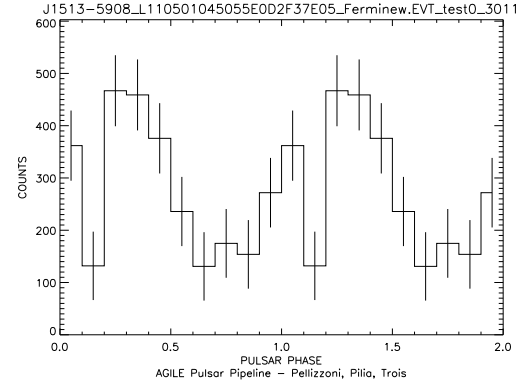


FIG. 2: *Fermi*-LAT phase-aligned gamma-ray light curve of PSR B1509-58 at energies  $< 150$  MeV, with radio peak at phase 0.

where we quote in parentheses (here and throughout the paper) the  $1\sigma$  error on the last digit. The first peak is coincident in phase with *COMPTEL*'s peak [23]. In its highest energy band (10-30 MeV) *COMPTEL* showed the indication of a second peak (even though the modulation had low significance,  $2.1\sigma$ ). This second peak is coincident in phase with *AGILE*'s second peak (Fig. 1). *AGILE* thus confirms the previously marginal detection of a second peak.

We also analyzed *Fermi*-LAT data in the same interval as covered by the *AGILE* observations and the radio ephemeris: from the beginning of the mission until October 2009 (longer than in the published analysis from the *Fermi*-LAT Collaboration, [1]). *Fermi*-LAT data were extracted through the Science Support Center[51] from a region of interest (ROI) of 15 degrees, but only a 5 degrees extraction radius was used for the timing analysis. We selected the events and the correct time intervals using the Science Tools. We used the "diffuse" class events (highest probability of being gamma-ray photons) under the P6\_V3 instrument response function (IRFs), and excluded events with zenith angles  $> 105^\circ$  to reject atmospheric gamma-rays from the Earth's limb. The events were selected using the standard software package *Science Tools-09-21-00* for the *Fermi*-LAT data analysis: in particular *gtselect* and *gtmktime* for the selection of photons and time intervals, and *gtbary* to barycenter the photons. The actual photon folding is done using the *AGILE* software for pulsar observations. The resulting light curve in the soft energy band ( $E < 150$  MeV) are presented in Fig. 2 and it clearly shows two peaks.

Fig. 3 shows the SED of PSR B1509-58 based on *AGILE*'s and *COMPTEL*'s observed fluxes. *Fermi*-LAT upper limits from [1] are also shown, which are consistent with our measurements at a  $2\sigma$  confidence level. *COMPTEL* observed this pulsar in three energy bands: 0.75-3 MeV, 3-10 MeV, 10-30 MeV, suggesting a spectral break between 10 and 30 MeV. *AGILE*

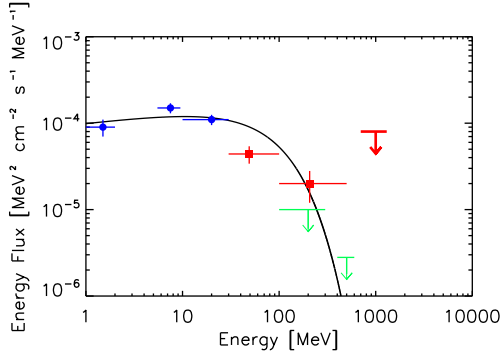


FIG. 3: SED of PSR B1509-58 (solid line) obtained from a fit of pulsed fluxes from soft to hard gamma-rays. The three round points represent *COMPTEL* observations [23]. The two square points represent *AGILE* pulsed flux in two bands ( $30 < E < 100$  MeV and  $100 < E < 500$  MeV). The thicker arrow represents *AGILE* upper limit above 500 MeV. The two thin arrows represent *Fermi* upper limits from [1]

pulsed flux confirms the presence of a soft spectral break. As shown in Fig. 3, we modeled the observed *COMPTEL* and *AGILE* fluxes with a power-law plus cutoff fit using the Minuit minimization package (James et al. 1975):  $F(E) = k \times E^{-\alpha} \exp[-(E/E_c)^\beta]$ , with three free parameters: the normalization  $k$ , the spectral index  $\alpha$ , the cutoff energy  $E_c$  and allowing  $\beta$  to assume values of 1 and 2 (indicating either an exponential or a superexponential cutoff). No acceptable  $\chi^2$  values were obtained for a superexponential cutoff, the presence of which can be excluded at a  $3.5\sigma$  confidence level, while for an exponential cutoff we found  $\chi^2_\nu = 3.2$  for  $\nu = 2$  degrees of freedom, corresponding to a null hypothesis probability of 0.05. The best values thus obtained for the parameters of the fit were:  $k = 1.0(2) \times 10^{-4} \text{ s}^{-1} \text{ cm}^{-2}$ ,  $\alpha = 1.87(9)$ ,  $E_c = 81(20) \text{ MeV}$ .

### III. DISCUSSION

The bulk of the spin-powered pulsar flux is usually emitted in the MeV-GeV energy band with spectral breaks at  $\leq 10 \text{ GeV}$  (e.g. [2]). PSR B1509-58 has the softest spectrum observed among gamma-ray pulsars, with a sub-GeV cutoff at  $E \approx 80 \text{ MeV}$ . In the following we discuss how the new *AGILE* observations can constrain the models for emission from the pulsar magnetosphere (for an extended discussion see [35]).

When PSR B1509-58 was detected in soft gamma-rays but not significantly at  $E > 30 \text{ MeV}$ , it was proposed that the mechanism responsible for this low-energy spectral break might be photon splitting [17]. The photon splitting [3] is a third-order quantum electro-dynamics process expected when the magnetic field approaches or exceeds the *critical* value defined

as  $B_{cr} = m_e^2 c^3 / (e \hbar) = 4.413 \times 10^{13} \text{ G}$ . Most current theories for the generation of coherent radio emission in pulsar magnetospheres require formation of an electron-positron pair plasma developing via electromagnetic cascades. In very high magnetic fields the formation of pair cascades can be altered by the process of photon splitting:  $\gamma \rightarrow \gamma\gamma$ , which will operate as an attenuation mechanism in the high-field regions near pulsar polar caps. Since it has no energy threshold, photon splitting can attenuate photons below the threshold for pair production, thus determining a spectral cutoff at lower energies.

In the case of PSR B1509-58 a polar cap model with photon splitting would be able to explain the soft gamma-ray emission and the low energy spectral cutoff, now quantified by *AGILE* observations. Based on the observed cutoff, which is related to the photons' saturation escape energy, we can derive constraints on the magnetic field strength at emission, in the framework of photon splitting:

$$\epsilon_{esc}^{sat} \simeq 0.077 (B' \sin \theta_{kB,0})^{-6/5} \quad (1)$$

where  $\epsilon_{esc}^{sat}$  is the photon saturation escape energy,  $B' = B/B_{cr}$  and  $\theta_{kB,0}$  is the angle between the photon momentum and the magnetic field vectors at the surface and is here assumed to be very small:  $\theta_{kB,0} \leq 0.57^\circ$  (see [17]). Using the observed energy cutoff ( $\epsilon_{esc}^{sat} \simeq E = 80 \text{ MeV}$ ) we find that  $B' \geq 0.3$ , which implies an emission altitude  $\leq 1.3 R_{NS}$ , which is the height where possibly also pair production could ensue. This altitude of emission agrees with the polar cap models (see e.g. [10]). A smaller energy cutoff, as in [17], would have implied even lower emission altitude and a sharper break, possibly caused by the total absence of pair production. It is apparent that small differences in the emission position will cause strong differences in spectral shape. This is possibly the reason for the different emission properties of the two peaks as observed in the total (*AGILE* plus *COMPTEL*) gamma-ray energy band and confirmed by our reanalysis of *Fermi*-LAT data where this peaks clearly appears in the soft energy band. Also, a trend can be observed, from lower to higher energies (see the X-ray light-curve for the trend in the first peak, as in Fig. 3 of [23]), of the peaks slightly drifting away from the radio peak. This we assume to be another signature of the fact that small variations in emission height can be responsible for sensible changes in the light curves in such a high magnetic field. The scenario proposed by [17] is strengthened by its prediction that PSR B0656+14 should have a cutoff with an intermediate value between PSR B1509-58 and the other gamma-ray pulsars. Additionally, PSR B1509-58 [9, 23] and PSR B0656+14 [11, 47] show evidence of an aligned geometry, which could imply polar cap emission.

The polar cap model as an emission mechanism is debated. From the theoretical point of view, the an-

gular momentum is not conserved in polar cap emission (see [43] for a revision). Also, a preferential explanation of the observed gamma-ray light curves with high altitude cascades comes from the recent results by *Fermi*-LAT [2]. In the case of PSR B1509–58, the derived gamma-ray luminosity from the flux at  $E > 1$  MeV, considering a 1 sr beam sweep is  $L_\gamma = 4.2^{+0.5}_{-0.2} d_{5.2}^2 \times 10^{35}$  erg/s, where  $d_{5.2}$  indicates the distance in units of 5.2 kpc. While traditionally the beaming fraction ( $f_\Omega$ ) was considered to be the equivalent of a 1 sr sweep, nowadays (see e.g. [46]) the tendency is to consider a larger beaming fraction ( $f_\Omega \approx 1$ ), close to a  $4\pi$  sr beam. Using  $f_\Omega = 1$  in our calculations, we would have obtained  $L_\gamma = 5.8^{+0.1}_{-0.8} d_{5.2}^2 \times 10^{36}$  erg s $^{-1}$ . Thus the maximum conversion efficiency of the rotational energy loss ( $\dot{E} \approx 1.8 \times 10^{37}$  erg s $^{-1}$ ) into gamma-ray luminosity is 0.3. Our result is not easily comparable with the typical gamma-ray luminosities above 100 MeV, because for PSR B1509–58 this energy band is beyond the spectral break. Using *AGILE* data alone we obtained a luminosity above 30 MeV  $L_\gamma = 5.2(6) d_{5.2}^2 \times 10^{35}$  erg/s, again for a 1 sr beam. If the gamma-ray luminosity cannot account for a large fraction of the rotational energy loss, then the angular momentum conservation objection becomes less cogent for this pulsar, exactly as it happens for the radio emission.

Alternatively, if such an efficiency as that of PSR B1509–58 were incompatible with this conservation law, an interpretation of PSR B1509–58 emission can be sought in the frame of the three dimensional outer gap model [50]. According to their model, hard X-rays and low energy gamma-rays are both produced by synchrotron self-Compton radiation of secondary  $e^+e^-$  pairs of the outer gap. Therefore, as observed, the phase offset of hard X-rays and low energy gamma-rays with respect to the radio pulse is the same, with the possibility of a small lag due to the thickness of the emission region. According to their estimates a magnetic inclination angle  $\alpha \approx 60^\circ$  and a viewing angle  $\zeta \approx 75^\circ$  are required to reproduce the observed light curve. Finally, using the simulations of [46], who produced a map of pulse profiles for different combinations of angles  $\alpha$  and  $\zeta$  in the different emission models, the observed light curve from *AGILE* is best reproduced if  $\alpha \approx 35^\circ$  and  $\zeta \approx 90^\circ$ , in the framework of the two pole caustic model [13].

The values of  $\alpha$  and  $\zeta$  required by the [50] model are not in good agreement with the corresponding values obtained with radio measurements. In fact, [9] observe that  $\alpha$  must be  $< 60^\circ$  at the  $3\sigma$  level. The prediction obtained by the simulations of [46] better agrees with the radio polarization observations. In fact, in the framework of the rotating vector model (RVM, see e.g. [25] and references therein), [9] also propose that, if the restriction is imposed that  $\zeta > 70^\circ$  [29], then  $\alpha > 30^\circ$  at the  $3\sigma$  level. For these values, however, the Melatos model for the spin down of an oblique rotator predicts a braking index  $n > 2.86$ , slightly inconsistent with the observed value ( $n = 2.839(3)$ , see [24]). Also in the case of PSR B0656+14, [47] conclude that the large values of  $\alpha$  and  $\zeta$  are somewhat at odds with the constraints from the modeling of the radio data and the thermal X-rays which seem to imply a more aligned geometry. Improved radio polarization measurements would help placing better constraints on the pulsar geometry and therefore on the possibility of a gap in the extended or outer magnetosphere, but the quality of the polarization measurements from [9] is already excellent, the problem being that PSR B1509–58, like most pulsars, only shows emission over a limited pulse phase range and therefore the RVM models are highly degenerate.

At present the geometry privileged by the state of the art measurements is best compatible with polar cap models. Higher statistics in the number of observed gamma-ray pulsars could help characterize a class of "outliers" having gamma-ray emission from the polar caps, which potentially constitute a privileged target for *AGILE*.

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- [1] Abdo, A. A., et al. 2010, ApJ, 714, 927
  - [2] —. 2010, ApJS, 187, 460
  - [3] Adler, S. L., Bahcall, J. N., Callan, C. G., & Rosenbluth, M. N. 1970, Physical Review Letters, 25, 1061
  - [4] Aharonian, F., et al. 2005, A&A, 435, L17
  - [5] Aliu, E., et al. 2008, Science, 322, 1221
  - [6] Bai, X., & Spitkovsky, A. 2010, ApJ, 715, 1282
  - [7] Cheng, K. S., Ho, C., & Ruderman, M. 1986, ApJ, 300, 500
  - [8] Cohen, R. H., & Treves, A. 1972, A&A, 20, 305
  - [9] Crawford, F., Manchester, R. N., & Kaspi, V. M. 2001, AJ, 122, 2001
  - [10] Daugherty, J. K., & Harding, A. K. 1996, ApJ, 458, 278
  - [11] De Luca, A., Caraveo, P. A., Mereghetti, S., Negroni, M., & Bignami, G. F. 2005, ApJ, 623, 1051

- [12] Du, Y., Qiao, G. J., Han, J. L., Lee, K. J., & Xu, R. X. 2010, ArXiv e-prints
- [13] Dyks, J., & Rudak, B. 2003, ApJ, 598, 1201
- [14] Fierro, J. M. 1995, PhD thesis, Thesis, Stanford University, (1995)
- [15] Gaensler, B. M., Arons, J., Kaspi, V. M., Pivovarov, M. J., Kawai, N., & Tamura, K. 2002, ApJ, 569, 878
- [16] Gaensler, B. M., Brazier, K. T. S., Manchester, R. N., Johnston, S., & Green, A. J. 1999, MNRAS, 305, 724
- [17] Harding, A. K., Baring, M. G., & Gonthier, P. L. 1997, ApJ, 476, 246
- [18] Hobbs, G., Lyne, A. G., Kramer, M., Martin, C. E., & Jordan, C. 2004, MNRAS, 353, 1311
- [19] Hobbs, G. B., Edwards, R. T., & Manchester, R. N. 2006, MNRAS, 369, 655
- [20] Holloway, N. J. 1977, MNRAS, 181, 9P
- [21] James, F., & Roos, M. 1975, Computer Physics Communications, 10, 343
- [22] Kawai, N., Okayasu, R., Brinkmann, W., Manchester, R., Lyne, A. G., & D'Amico, N. 1991, ApJL, 383, L65
- [23] Kuiper, L., Hermsen, W., Krijger, J. M., Bennett, K., Carramiñana, A., Schönfelder, V., Bailes, M., & Manchester, R. N. 1999, A&A, 351, 119
- [24] Livingstone, M. A., Kaspi, V. M., Gavril, F. P., & Manchester, R. N. 2005, ApJ, 619, 1046
- [25] Lorimer, D. R., & Kramer, M. 2004, Handbook of Pulsar Astronomy (Cambridge, UK: Cambridge University Press)
- [26] Manchester, R. N., Tuohy, I. R., & Damico, N. 1982, ApJL, 262, L31
- [27] Mattox, J. R., et al. 1996, ApJ, 461, 396
- [28] Matz, S., et al. 1994, ApJ, 434, 288
- [29] Melatos, A. 1997, MNRAS, 288, 1049
- [30] Mineo, T., Cusumano, G., Maccarone, M. C., Massaglia, S., Massaro, E., & Trussoni, E. 2001, A&A, 380, 695
- [31] Muslimov, A. G., & Harding, A. K. 2003, ApJ, 588, 430
- [32] Pellizzoni, A., et al. 2009, ApJL, 695, L115
- [33] —. 2009, ApJ, 691, 1618
- [34] —. 2010, Science, 327, 663
- [35] Pilia, M., et al. 2010, ApJ, 723, 707
- [36] Pittori, C., et al. 2009, A&A, 506, 1563
- [37] Romani, R. W. 1996, ApJ, 470, 469
- [38] Sako, T., et al. 2000, ApJ, 537, 422
- [39] Seward, F. D., & Harnden, Jr., F. R. 1982, ApJL, 256, L45
- [40] Tamura, K., Kawai, N., Yoshida, A., & Brinkmann, W. 1996, PASJ, 48, L33
- [41] Tavani, M., et al. 2009, A&A, 502, 995
- [42] Thompson, D. J. 2004, in Astrophysics and Space Science Library, Vol. 304, Cosmic Gamma-Ray Sources, ed. K. S. Cheng & G. E. Romero, 149
- [43] Treves, A., Pilia, M., & Moya, M. L. 2011, in American Institute of Physics Conference Series, Vol. 1357, American Institute of Physics Conference Series, 312–313
- [44] Trussoni, E., Massaglia, S., Caucino, S., Brinkmann, W., & Aschenbach, B. 1996, A&A, 306, 581
- [45] Ulmer, M. P., et al. 1993, ApJ, 417, 738
- [46] Watters, K. P., Romani, R. W., Weltevrede, P., & Johnston, S. 2009, ApJ, 695, 1289
- [47] Weltevrede, P., et al. 2010, ApJ, 708, 1426
- [48] —. 2010, Publications of the Astronomical Society of Australia, 27, 64
- [49] Wilson, R. B., & et al. 1993, in Isolated Pulsars, ed. K. A. van Riper, R. I. Epstein, & C. Ho, 257
- [50] Zhang, L., & Cheng, K. S. 2000, A&A, 363, 575
- [51] See <http://fermi.gsfc.nasa.gov/ssc/> also for the following.